

# 3 energibalanse.pdf

Energibalanse, modellering, termisk energi, spesifikk varmekapasitet, varmetransport relatert til massestrøm, spesifikt varmeovergangstall, varmeovergang (tvungen konveksjon), blokkdiagram, simulering:

RST:

- Termofysikk, kap 7 side 187-189.

EUP:

- Temperature and heat, kap 16.2, 16.4

Lærebok:

- Termiske systemer, kap 2.5

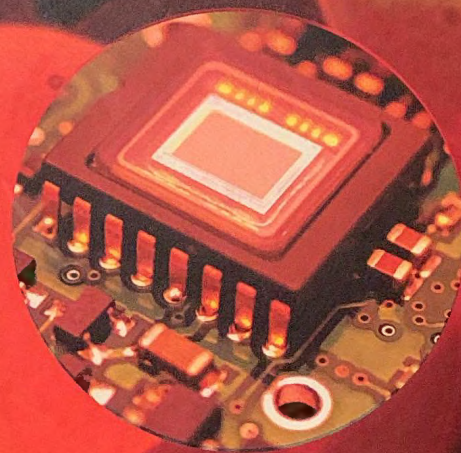
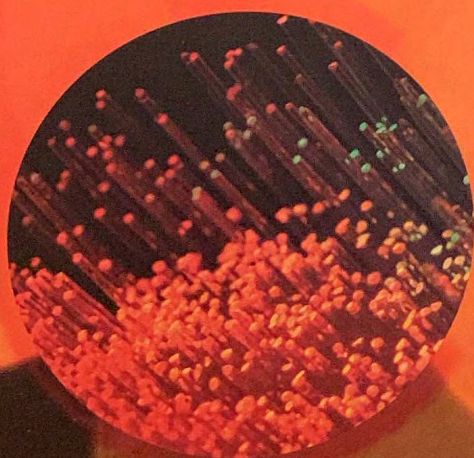


GRUNNBOK

Arne Auen Grimenes • Per Jerstad • Bjørn Sletbak

# Rom Stoff Tid

FYSIKK FORKURS



CAPPELEN DAMM

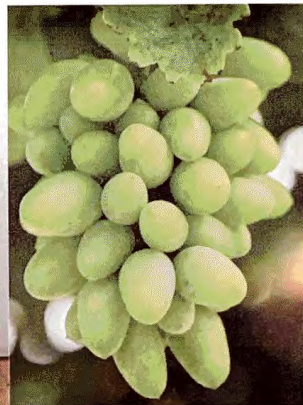


# 7 Termofysikk

Energi er en forutsetning for liv. For at levende organismer skal kunne bestå og utvikle seg, må de utveksle energi med omgivelsene. Utveksling av energi ved varme er det termofysikken handler om.

Men termofysikken gir ikke bare grunnlaget for å forstå denne energiutvekslingen. Vi trenger termofysikk for å kunne forstå den teknologiske energiomdanningen som er forutsetningen for samfunnet vi lever i. Verdens energiforsyning baserer seg i all hovedsak på energi fra varmekilder, enten det er fra brennende gass/olje/kull, fra sol, fra atomenergi, eller det er fra ved eller annen bioenergi.

De fleste av verdens energiverk for produksjon av elektrisk energi høster av disse varmekildene. Også motoren, som er en forutsetning for vår sivilisasjon, har varme som energikilde. Vi klarer oss ikke uten bensinmotorer, dieselmotorer og gasturbiner.



Men vi vet at bruk av varme fra fossile brennstoffer for å drive alle disse motorene og elektrisitetsverkene, skaper store miljøproblemer. Dermed er kunnskap om termofysikk også viktig for alle som vil forstå og være med og løse de miljøproblemene som er knyttet til produksjon og bruk av energi.

De viktigste resultatene av termofysikken er uttrykt i to lover, termofysikkens 1. og 2. lov. Det er dem vi skal studere nærmere i dette kapittelet.

# Kalorimetri

Måling og beregning av varme og endring av indre energi i legemer og stoffer kaller vi kalorimetri. Vi skal nå se på de sentrale størrelsene og metodene i denne delen av varmelæra.

## Varmekapasitet

På side 185 så vi at varmen som vi tilfører et stoff, er proporsjonal med temperaturøkningen i stoffet. Videre er varmen proporsjonal med hvor mye stoff vi har, siden dobbelt så mye stoff nødvendigvis krever dobbelt så mye varme for samme temperaturøkning.

Varmen  $Q$  som må tilføres for at temperaturen skal stige fra  $t_1$  til  $t_2$ , er altså proporsjonal med *både* massen  $m$  og med temperaturøkningen  $\Delta t = t_2 - t_1$ :

$$Q = cm\Delta t$$

Proporsjonalitetskonstanten  $c$  i likningen er bestemt av hvilket stoff legemet er lagd av. Den er en materialkonstant (i likhet med massetettheten  $\rho$ ), og vi kaller denne konstanten *den spesifikke varmekapasiteten* til stoffet.

Varmen  $Q$  som trengs for å øke temperaturen i et legeme med  $\Delta t = t_2 - t_1$ , er gitt ved

$$Q = cm\Delta t$$

der  $m$  er massen til legemet og  $c$  er den spesifikke varmekapasiteten.

Den spesifikke varmekapasiteten er altså definert som

$$c = \frac{Q}{m\Delta t}$$

Dermed blir SI-enheten for spesifikk varmekapasitet J/(kgK). Tabellen i margen viser den spesifikke varmekapasiteten for en del stoffer.

Er det egentlig noen forskjell på tabellen nederst på side 185 og tabellen i margen her (bortsett fra antallet stoffer)?



Uttrykket  $Q = cm\Delta t$  kan vi også bruke når legemet gir fra seg varme ved avkjøling. Da er  $\Delta t = t_2 - t_1$ , og dermed  $Q$ , negativ. Men i eksempler og oppgaver som har med varmekapasitet å gjøre, regner vi som regel uten fortegn. Når vi bruker likningen  $Q = cm\Delta t$ , lar vi derfor  $t_2$  være den høyeste temperaturen.

### Spesifikk varmekapasitet $c$

ved 25 °C og normaltrykk.

	kJ/(kgK)
Bly	0,13
Sølv	0,24
Jern	0,45
Aluminium	0,90
Kopper	0,39
Sink	0,39
Glass	0,84
Luft	1,0
Is	2,1
Vann	4,2
Vanndamp	2,0
Menneskekropp	3,5

### Spesifikk varmekapasitet



## EKSEMPEL 7.3

Et legeme av glass har massen 10 kg og avkjøles fra 35 °C til -15,0 °C. Hvor mye varme avgir glasset ved denne avkjølingen?

**Løsning:**

Vi finner den spesifikke varmekapasiteten for glass i en fysikktabell og får

$$\begin{aligned} Q &= cm\Delta t \\ &= 0,84 \text{ kJ}/(\text{kgK}) \cdot 10 \text{ kg} \cdot (35 \text{ °C} - (-15,0 \text{ °C})) \\ &= 8,4 \text{ kJ/K} \cdot 50 \text{ K} = \underline{0,42 \text{ MJ}} \end{aligned}$$



Den spesifikke varmekapasiteten for vann er stor i forhold til verdien for andre stoffer. Det betyr at vann kan ta opp og lagre store energimengder. Kan du tenke deg forhold i naturen eller forhold knyttet til teknologi der denne egenskapen hos vann er viktig?



Når vi tar en nysteikt pizza ut av ovnen, blir pizzabunnen avkjølt ganske raskt slik at vi kan holde pizzaen uten å brenne oss. Men vi kan likevel fort brenne tunga på pizzasausen. Hvorfor?

**Varmekapasiteten til et legeme**

For legemer som er satt sammen av mange forskjellige stoffer, kjenner vi ikke den spesifikke varmekapasiteten. Men det må fortsatt være slik at den tilførte varmen er proporsjonal med temperaturøkningen:

$$Q = C\Delta t$$

Proporsjonalitetskonstanten  $C$  i denne likningen kalles *varmekapasiteten* til legemet (altså ikke spesifikk). Den tilførte varmen  $Q$  dividert med temperaturstigningen  $\Delta t$  er dermed lik varmekapasiteten til legemet:

$$C = \frac{Q}{\Delta t}$$

Enheten for varmekapasitet blir da J/K. I eksempel 7.3 ser du i siste linje i utregningen at varmekapasiteten for *hele* glasset er 8,4 kJ/K.

## EKSEMPEL 7.4

Det trengs en varme på 200 J for å øke temperaturen i en termosflaske med 4,0 K.

Finn varmekapasiteten til termosflaska.

**Løsning:**

$$C = \frac{Q}{\Delta t}$$

$$= \frac{200 \text{ J}}{4,0 \text{ K}} = \underline{60 \text{ J/K}}$$

Når vi skal måle den spesifikke varmekapasiteten for en væske, passer det å bruke en beholder med lite varmetap, for eksempel en termosflaske. En slik varmemåler blir også kalt et *kalorimeter* (fra latin calor = varme).

## EKSEMPEL 7.5

Vi har 200 g av en væske i en termosflaske og varmer opp med et elektrisk varmeelement. Når varmeelementet leverer 7,00 kJ, øker temperaturen i vannet og termosflaska fra 15,2 °C til 28,0 °C. Varmekapasiteten til termosflaska er 50 J/K.

- Finn den spesifikke varmekapasiteten for væsken.
- Bruk fysikktabellen til å avgjøre hvilken væske det kan være.

**Løsning:**

- Vannet mottar varmen  $Q_v = c_v m_v \Delta t$ , og kalorimeteret mottar varmen  $Q_k = C_k \Delta t$ . Vi antar at det ikke er noen varmeutveksling med omgivelsene. Da er summen av mottatt varme lik den tilførte energien. Varmeelementet tilfører energien  $E = 7,00 \text{ kJ}$ .

Mottatt varme = tilført energi

$$Q_v + Q_k = E$$

$$c_v m_v \Delta t + C_k \Delta t = E$$

$$c_v m_v \Delta t = E - C_k \Delta t$$

$$c_v = \frac{E}{m_v \Delta t} - \frac{C_k}{m_v}$$

$$= \frac{7,00 \cdot 10^3 \text{ J}}{0,200 \text{ kg} \cdot (28,0 - 15,2) \text{ K}} - \frac{50 \text{ J/K}}{0,200 \text{ kg}} = \underline{2,5 \text{ kJ/(kgK)}}$$

- I fysikktabellen finner vi at etanol har spesifikk varmekapasitet 2,45 kJ/(kgK), og at glyserol har 2,43 kJ/(kgK). Sannsynligvis er væsken enten etanol eller glyserol.





GLOBAL  
EDITION



# Essential University Physics

## Volume 1

THIRD EDITION

Richard Wolfson

ALWAYS LEARNING

PEARSON



# Temperature and Heat

## What You Know

- You understand the concept of *energy*, especially *kinetic* and *potential energy*.
- You've had a brief introduction to *internal energy*.
- You recognize that *power* is a rate of energy use, flow, conversion, and so on.
- You're familiar with *pressure* and *density* from your study of fluids in Chapter 15.

## What You're Learning

- You'll refine your everyday notions of *temperature* and *heat*, honing them into precise physics definitions.
- You'll learn about temperature scales and how they're established.
- You'll see how a material's *specific heat* determines the energy needed to change its temperature.
- You'll learn three mechanisms of heat transfer: *conduction*, *convection*, and *radiation*.
- You'll see how a system's temperature is determined by *thermal-energy balance* with its surroundings, with application to systems ranging from buildings to planetary climates.

## How You'll Use It

- The ideas in this chapter will serve as the groundwork for your study of thermodynamics in Chapters 17, 18, and 19.
- Thermodynamics will have many applications in subsequent work you might do in engineering, environmental science, biology, chemistry, and physics.



How does this infrared photo reveal heat loss from the house? And how can you tell that the car was recently driven?

**Y**our own body gives you a good sense of “hot” and “cold.” Questions about heat and temperature are ultimately about energy, and these concepts are crucial to understanding the energy flows that drive natural systems like Earth’s climate and technologies such as engines, power plants, and refrigerators.

Properties like mass and kinetic energy apply equally to microscopic atoms and molecules and to cars and planets. But other properties, including temperature and pressure, apply only to macroscopic systems. It makes no sense to talk about the temperature or pressure of a single air molecule. **Thermodynamics** is the branch of physics that deals with these macroscopic properties. Ultimately, the thermodynamic behavior of matter follows from the motions of its constituent particles in response to the laws of mechanics. **Statistical mechanics** relates the macroscopic description of matter to the underlying microscopic processes. Historically, thermodynamics developed before the atomic theory of matter was fully established. The subsequent explanation of thermodynamics through statistical mechanics—the mechanics of atoms and molecules—was a triumph for physics.

## 16.1 Heat, Temperature, and Thermodynamic Equilibrium

Take a bottle of soda from the refrigerator, and eventually it reaches room temperature. At that point the soda and the room are in **thermodynamic equilibrium**, a state in which their macroscopic properties are no longer changing. To check for thermodynamic equilibrium we can consider any macroscopic property—length, volume, pressure, electrical resistance, whatever. If any macroscopic property changes



Systems A and C are each in thermodynamic equilibrium with B.

If A and C are placed in thermal contact, their macroscopic properties don't change—showing that they're already in equilibrium.

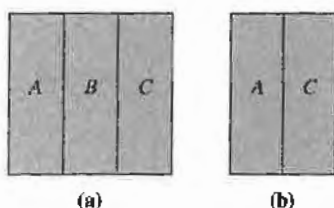


FIGURE 16.1 The zeroth law of thermodynamics.

when two systems are placed together, then they weren't originally in thermodynamic equilibrium. When changes cease, the systems have reached equilibrium.

The phrase “placed together” here has a definite meaning, stated more precisely as “placed in thermal contact.” Two systems are in **thermal contact** if heating one of them results in macroscopic changes in the other. If that doesn't readily happen—for example, with a Styrofoam cup of coffee and its surroundings—then the systems are **thermally insulated**.

We can now begin to define temperature: **Two systems have the same temperature if they are in thermodynamic equilibrium.** Consider two systems A and C in thermal contact with a third system B but not with each other (Fig. 16.1a). Even though they're not in direct contact, A and C have the same temperature; that is, if you place A and C in thermal contact (Fig. 16.1b), no further changes occur. This fact—that two systems in equilibrium with a third system are therefore in equilibrium with each other—is so fundamental that it's called the **zeroth law of thermodynamics**.

A **thermometer** is a system with a conveniently observed macroscopic property that changes with temperature. It could be the length of a mercury column, gas pressure, electrical resistance, or the bending of a bimetal strip in a dial thermometer. Let the thermometer come to equilibrium with some system, and its temperature-dependent physical property provides a measure of temperature. The zeroth law assures consistency, in that two systems for which the thermometer gives the same reading must have the same temperature.

## The Kelvin Scale and Gas Thermometers

One of the most versatile thermometers is the **constant-volume gas thermometer** (Fig. 16.2), in which the pressure of a gas provides an indication of temperature. Gas thermometers function over a wide range, including very low temperatures, and they currently provide the definition of the Kelvin temperature scale used in the SI system. As Fig. 16.3 shows, the zero of the Kelvin scale is defined as the temperature at which the gas pressure would become zero. Since a gas can't have negative pressure, this point is defined as **absolute zero**—a concept whose meaning we'll explore further in Chapter 19. A second fixed temperature is provided by the so-called triple point of water, the unique temperature at which solid, liquid, and gaseous water can coexist in equilibrium (more on this in Chapter 17). In the current SI definition, water's triple point is defined to be exactly 273.16 kelvin (symbol K; *not* “degrees kelvin or °K”). Other temperatures then followed by linear extrapolation, as suggested in Fig. 16.3. Although the triple-point definition of the kelvin is, in principle, a reproducible operational standard, issues with purity and the isotopic composition of water have made this standard less than ideal.

In the ongoing revision of the SI unit system, the kelvin will be given a new explicit-constant definition, by setting an exact value for the so-called Boltzmann constant. This constant establishes a direct relation between temperature and molecular energy, which we'll explore further in Chapter 17. With this new definition, the triple point of water becomes a measured quantity very close to 273.16 K but, as with all measured quantities, involving some uncertainty.

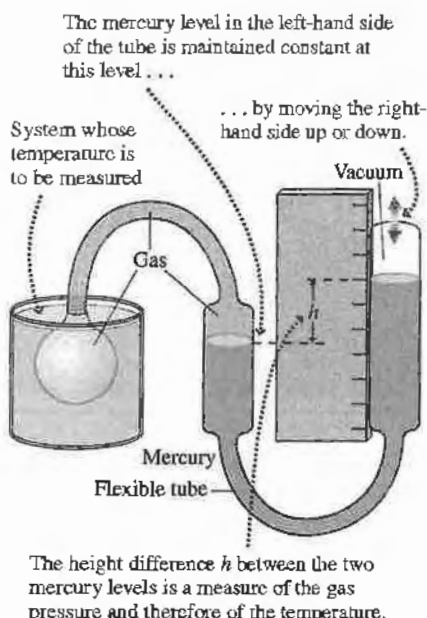
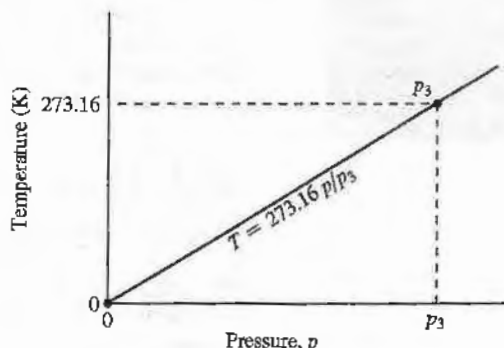


FIGURE 16.2 A constant-volume gas thermometer.

FIGURE 16.3 Two points establish a temperature scale. Until the ongoing SI revision is complete, the kelvin scale is defined by the values of absolute zero and the unique temperature of water's triple point, whose pressure is designated  $p_3$  and whose temperature is defined as 273.16 K.

## Temperature Scales

Other temperature scales include Celsius ( $^{\circ}\text{C}$ ), Fahrenheit ( $^{\circ}\text{F}$ ), and Rankine ( $^{\circ}\text{R}$ ) (Fig. 16.4). One Celsius degree represents the same temperature difference as one kelvin, but the zero of the Celsius scale occurs at 273.15 K, so

$$T_{\text{C}} = T - 273.15 \quad (16.1)$$

where  $T$  is the temperature in kelvins. On the Celsius scale the melting point of ice at standard atmospheric pressure is exactly  $0^{\circ}\text{C}$ , while the boiling point is  $100^{\circ}\text{C}$ . The triple point of water occurs at  $0.01^{\circ}\text{C}$ , which accounts for the 273.15 difference between the kelvin and Celsius scales. Equation 16.1 shows that absolute zero occurs at  $-273.15^{\circ}\text{C}$ .

The Fahrenheit and Rankine scales, from the British unit system, are used primarily in the United States. Fahrenheit has water melting at  $32^{\circ}\text{F}$  and boiling at  $212^{\circ}\text{F}$ , so the relation between Fahrenheit and Celsius temperatures is

$$T_{\text{F}} = \frac{9}{5}T_{\text{C}} + 32 \quad (16.2)$$

A Rankine degree is the same size as a Fahrenheit degree, but the zero of the Rankine scale is at absolute zero (Fig. 16.4). Engineers in the United States often use Rankine.

## Heat and Temperature

A match will burn your finger, but it doesn't provide much heat. This example shows our intuitive sense of temperature and heat: Heat measures an *amount* of "something," whereas temperature is the *intensity* of that "something."

Scientists once considered heat to be a material fluid, called **caloric**, that flowed from hot bodies to colder ones. But in the late 1700s, the American-born scientist Benjamin Thompson observed essentially limitless amounts of heat being produced in the boring of cannon, and he concluded that heat could not be a conserved fluid. Instead, Thompson suggested, heat was associated with mechanical work done by the boring tool. In the next half-century, a series of experiments confirmed the association between heat and energy. These culminated in the work of the British physicist James Joule (1818–1889), who quantified the relation between heat and energy. In so doing, Joule brought thermal phenomena under the powerful conservation-of-energy principle. In recognition of this major synthesis in physics, the SI energy unit bears Joule's name. The redefinition of the kelvin will formalize the relation between temperature and energy, since the Boltzmann constant, which will establish the kelvin's definition, has the units of J/K.

We rarely make statements about the amount of "heat" in an object; we're more concerned that the temperature be appropriate. Rather, we think of heat as something that gets transferred from one object to another, causing a temperature change. The scientific definition reflects this sense of heat as energy in transit: **Heat is energy being transferred from one object to another because of a temperature difference alone.** Strictly speaking, heat refers only to energy in transit. Following heat transfer, we say that the **internal energy** or **thermal energy** of the object has increased, not that it contains more heat. This distinction reflects the fact that processes other than heating—such as transfer of mechanical or electrical energy—can also change an object's temperature. We briefly explored internal energy and its relation to mechanical energy transfers when we dealt with nonconservative forces in Chapter 7.

**GOT IT? 16.1** Is there (a) no temperature, (b) one temperature, or (c) more than one temperature where the Celsius and Fahrenheit scales agree?

## 16.2 Heat Capacity and Specific Heat

Because temperature and energy are related, it's not surprising that the heat energy  $Q$  transferred to an object and the resulting temperature change  $\Delta T$  are proportional:  $Q = C \Delta T$ , where the proportionality constant  $C$  is called the **heat capacity** of the object.

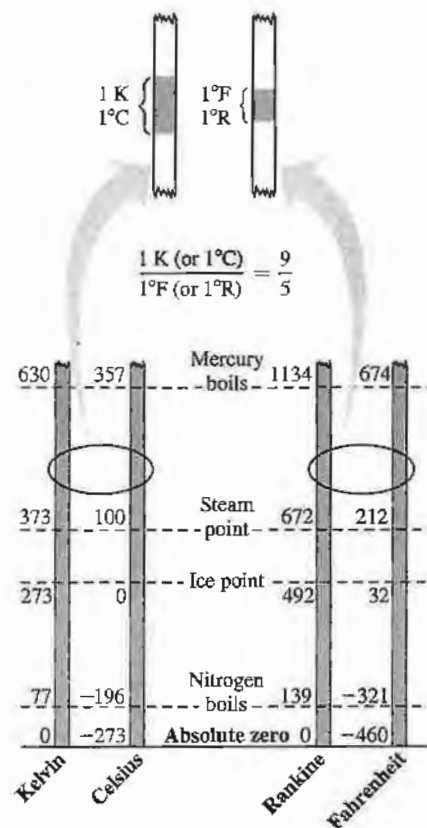


FIGURE 16.4 Relationships among four temperature scales.





Video Tutor Demo | Heating Water and Aluminum



Video Tutor Demo | Water Balloon Held over Candle Flame

Table 16.1 Specific Heats of Some Common Materials\*

Substance	Specific Heat, $c$	
	SI Units: J/kg·K	cal/g·°C, kcal/kg·°C, or Btu/lb·°F
Aluminum	900	0.215
Concrete (varies with mix)	880	0.21
Copper	386	0.0923
Iron	447	0.107
Glass	753	0.18
Mercury	140	0.033
Steel	502	0.12
Stone (granite)	840	0.20
Water:		
Liquid	4184	1.00
Ice, -10°C	2050	0.49
Wood	1400	0.33

\*Temperature range 0°C to 100°C except as noted.

Since heat is a measure of energy transfer, the units of heat capacity are J/K. The heat capacity  $C$  applies to a specific object and depends on its mass and on the substance from which it's made. We characterize different substances in terms of their **specific heat**  $c$ , or heat capacity per unit mass. The heat capacity of an object is then the product of its mass and specific heat, so we can write

$$Q = mc \Delta T \quad (16.3)$$

The SI units of specific heat are J/kg·K. Table 16.1 lists specific heats of common materials.

Scientists first studied thermodynamic phenomena before they knew the relation between heat and energy, and they used other units for heat. The **calorie** (cal) was defined as the heat needed to raise the temperature of 1 g of water from 14.5°C to 15.5°C; consequently, the specific heat of water is 1 cal/g·°C. Several different definitions of the calorie exist today, based on different methods for establishing the heat–energy equivalence. In this book we use the so-called thermochemical calorie, defined as exactly 4.184 J. The “calorie” used in describing the energy content of foods is actually a kilocalorie. In the British system, still widely used in engineering in the United States, the unit of heat is the **British thermal unit** (Btu). One Btu is the amount of heat needed to raise the temperature of 1 lb of water from 63°F to 64°F, and is equal to 1054 J.

### EXAMPLE 16.1 Specific Heat: Waiting to Shower

Your whole family has showered before you, dropping the temperature in the water heater to 18°C. If the heater holds 150 kg of water, how much energy will it take to bring it up to 50°C? If the energy is supplied by a 5.0-kW electric heating element, how long will that take?

**INTERPRET** Here we're interested in the energy it takes to raise the water temperature, so we interpret this problem as involving specific heat. For the second part, we're given the heater's power output and asked for the time, so we need to recall (Chapter 6) that power is energy per time.

**DEVELOP** Equation 16.3,  $Q = mc \Delta T$ , relates energy and temperature change via specific heat, so our plan is to calculate the required energy from this equation. We'll then use the relation between power and energy to find the time.

**EVALUATE** Equation 16.3 gives the energy:

$$Q = mc \Delta T = (150 \text{ kg})(4184 \text{ J/kg·K})(50^\circ\text{C} - 18^\circ\text{C}) = 20 \text{ MJ}$$

where we found the specific heat of water in Table 16.1. The heating element supplies energy at the rate of 5.0 kW or  $5.0 \times 10^3 \text{ J/s}$ . At that rate the time needed to supply 20 MJ is

$$\Delta t = \frac{2.0 \times 10^7 \text{ J}}{5.0 \times 10^3 \text{ J/s}} = 4000 \text{ s}$$

or a little over an hour.

**ASSESS** That's a long time to wait, but it's not an unreasonable answer!

**✓TIP** Is That °C or K?

It doesn't matter when we're talking about temperature *differences*. That's why we could mix units, multiplying the specific heat in J/kg·K by the difference of Celsius temperatures.

For common materials around room temperature, specific heat is nearly constant over a substantial temperature range. But at very low temperatures, specific heat varies significantly with temperature. When that's the case, we write Equation 16.3 in terms of infinitesimal heat flows  $dQ$  and corresponding temperature changes  $dT$ :  $dQ = mc(T) dT$ . We can then integrate to relate the overall heat flow and temperature change over a wide temperature range. Problems 73 and 74 explore this situation.

Specific heat also depends on whether an object's pressure or its volume changes when it's heated. For solids and liquids, which don't expand much, that distinction isn't very important. But it makes a big difference whether a gas is confined or allowed to expand when heated. Consequently, gases have two different specific heats, depending on whether volume or pressure is constant. We'll deal with that issue in Chapter 18, where we explore the thermodynamic behavior of gases.

## The Equilibrium Temperature

When objects at different temperatures are in thermal contact, heat flows from the hotter object to the cooler one until they reach thermodynamic equilibrium. If the objects are thermally insulated from their surroundings, then all the energy leaving the hotter object ends up in the cooler one. Mathematically, this statement reads

$$m_1 c_1 \Delta T_1 + m_2 c_2 \Delta T_2 = 0 \quad (16.4)$$

For the hotter object,  $\Delta T$  is negative, so the two terms in Equation 16.4 have opposite signs. One term represents the outflow of heat from the hotter object, the other inflow into the cooler one. Example 16.2 explores the application of Equation 16.4 in finding the equilibrium temperature.

**GOT IT? 16.2** A hot rock with mass 250 g is dropped into an equal mass of cool water. Which temperature changes more, that of (a) the rock or (b) the water? Explain.

### EXAMPLE 16.2 Finding the Equilibrium Temperature: Cooling Down

An aluminum frying pan of mass 1.5 kg is at 180°C when it's plunged into a sink containing 8.0 kg of water at 20°C. Assuming that none of the water boils and that no heat is lost to the surroundings, find the equilibrium temperature of the water and pan.

**INTERPRET** Here we have two objects, initially at different temperatures, that come to thermal equilibrium. So this is a problem about the equilibrium temperature, with the system of interest comprising the pan and the water.

**DEVELOP** Equation 16.4,  $m_1 c_1 \Delta T_1 + m_2 c_2 \Delta T_2 = 0$ , applies. However, we're asked for the common equilibrium temperature  $T$ , so we write the temperature differences  $\Delta T$  in terms of  $T$  and the initial temperatures  $T_p$  and  $T_w$  of pan and water. Equation 16.4 then becomes  $m_p c_p (T - T_p) + m_w c_w (T - T_w) = 0$ .

**EVALUATE** We now solve for the equilibrium temperature  $T$ :

$$T = \frac{m_p c_p T_p + m_w c_w T_w}{m_p c_p + m_w c_w}$$

Using the given values of  $m_p$ ,  $T_p$ ,  $m_w$ , and  $T_w$ , and taking  $c_p$  and  $c_w$  from Table 16.1, we get  $T = 26^\circ\text{C}$ .

**ASSESS** The water has much greater mass and higher specific heat, so it makes sense that its 6°C temperature change is a lot less than the 154°C drop in the pan's temperature. ■

## 16.3 Heat Transfer

How is heat transferred? Engineers need to know so they can design heating and cooling systems. Scientists need to know so they can anticipate temperature changes, as in global warming. Here we'll consider three common heat-transfer mechanisms: conduction, convection, and radiation. In some situations, a single mechanism dominates; in other cases, we may need to take all three into account.



**EXAMPLE 16.5** Calculating Radiation: The Sun's Temperature

The Sun radiates energy at the rate  $P = 3.9 \times 10^{26}$  W, and its radius is  $7.0 \times 10^8$  m. Treating the Sun as a blackbody ( $e = 1$ ), find its surface temperature.

**INTERPRET** This is a problem about the radiation from a hot object.

**DEVELOP** The Stefan-Boltzmann law, Equation 16.9, gives the radiated power in terms of the temperature, emissivity, and surface area:  $P = e\sigma AT^4$ . Our plan is to solve this equation for  $T$ . For the Sun, radiation comes from the entire spherical surface of area  $4\pi R^2$ , as our sketch shows (Fig. 16.11).

**EVALUATE** Using the Sun's spherical surface area and solving Equation 16.9 for  $T$  gives

$$T = \left( \frac{P}{4\pi R^2 \sigma} \right)^{1/4} = \left[ \frac{3.9 \times 10^{26} \text{ W}}{4\pi (7.0 \times 10^8 \text{ m})^2 (5.7 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)} \right]^{1/4} = 5.8 \times 10^3 \text{ K}$$

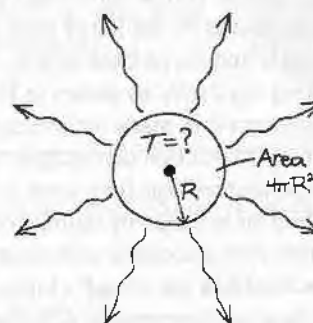


FIGURE 16.11 The Sun radiates from its spherical surface area  $4\pi R^2$ .

**ASSESS** Make sense? Yes: Our answer has the unit of temperature and agrees with observational measurements. Despite its bright glow, the Sun is essentially a blackbody, because it absorbs all radiation incident on it. But the Sun is so much hotter than its surroundings that we can neglect absorbed radiation in this calculation. ■

**CONCEPTUAL EXAMPLE 16.1** Energy-Saving Windows

Why do double-pane windows reduce heat loss greatly compared with single-pane windows? Why is a window's  $\mathcal{R}$ -factor higher if the spacing between panes is small? And why do the best windows have "low-E" coatings?

**EVALUATE** Table 16.2 gives glass's thermal conductivity as around  $0.8 \text{ W/m} \cdot \text{K}$ , while good insulators like air and Styrofoam have  $k \sim 0.03 \text{ W/m} \cdot \text{K}$ . That's why a layer of air between window panes greatly increases the window's  $\mathcal{R}$ -factor. But if the pane spacing is too great, convection currents develop between the sheets of glass, transferring heat from the warmer to the cooler surface; that's why narrower pane spacing is better. Finally, warm glass loses energy by radiation, and a thin coating of material with low emissivity ("low-E") reduces radiant heat loss.

**ASSESS** High-quality windows include all three features described here, so they suppress all three kinds of heat loss we've discussed. The best windows also use an inert gas—usually argon—between panes to reduce heat loss further.

**MAKING THE CONNECTION** Compare the  $\mathcal{R}$ -factor for a single-pane window made from 3.0-mm-thick glass with that of a double-pane window made from the same glass with a 5.0-mm air gap between panes.

**EVALUATE** Compute the  $\mathcal{R}$ -factors for the glass and air space, and you'll get about  $0.004 \text{ m}^2 \cdot \text{K/W}$  for the single pane and, adding two layers of glass and the air space,  $0.2 \text{ m}^2 \cdot \text{K/W}$  for the double-pane window. That's a factor of 50 improvement! In English units our answers translate into  $\mathcal{R}$ -factors of 0.02 and 1.1—although again they're lower than for actual windows because they neglect "dead air" layers and the other improvements discussed above. The best commercially available windows, in fact, achieve  $\mathcal{R}$ -factors of 5 and higher, and some multilayer windows exceed  $\mathcal{R}$ -10.

## 16.4 Thermal-Energy Balance

You keep your house at a comfortable temperature in winter by balancing heat loss with energy from your heating system (Fig. 16.12). This state of **thermal-energy balance** occurs throughout science and engineering. Understanding thermal-energy balance enables engineers to specify a building's heat sources and helps scientists predict Earth's future climate.

Engineered systems actively control the thermal-energy balance to achieve a desired temperature. But even without active control, systems with a fixed rate of energy input naturally tend toward energy balance. That's because all heat-loss mechanisms give increased loss with increasing temperature. If the rate of energy input to a system is greater than the loss rate, then the system gains energy and its temperature increases—and so, therefore, does the loss rate. Eventually the two come to balance at some fixed temperature. If the

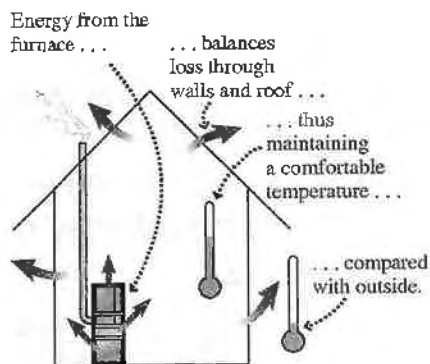


FIGURE 16.12 A house in thermal-energy balance.

loss exceeds the gain, the system cools until again it's in balance. Problems involving thermal-energy balance are similar regardless of the energy-loss mechanism or whether the application is to a technological or a natural system.

### PROBLEM-SOLVING STRATEGY 16.1 Thermal-Energy Balance

**INTERPRET** Interpret the problem to be sure it deals with heat gains and losses. Identify the system of interest, the source(s) of energy input to the system, and the significant heat-loss mechanism(s).

**DEVELOP** Determine which equation(s) govern the heat loss; these will necessarily involve the system's temperature. Your plan is then to equate the rate of energy loss with the rate of energy input.

**EVALUATE** Write an equation that expresses equality of energy loss and input. Then evaluate by solving for the quantity the problem asks for—often the system's temperature.

**ASSESS** If your answer is a temperature, does it seem reasonable? Is the temperature of a heated system higher than that of its surroundings?

### EXAMPLE 16.6 Thermal-Energy Balance: Hot Water

A poorly insulated electric water heater loses heat by conduction at the rate of 120 W for each Celsius degree difference between the water and its surroundings. It's heated by a 2.5-kW electric heating element and is located in a basement kept at 15°C. What's the water temperature if the heating element operates continuously?

**INTERPRET** The concept here is energy balance, and we identify the system of interest as the water. Its energy input comes from the heating element at the rate of 2.5 kW. The heat loss is by conduction.

**DEVELOP** Figure 16.13 is a sketch suggesting energy balance in the heater. We're given the conductive heat loss of 120 W/°C, meaning that the total heat-loss rate is  $H = (120 \text{ W/°C})(\Delta T)$ . We then equate the heat-loss rate to the energy-input rate:  $(120 \text{ W/°C})(\Delta T) = 2.5 \text{ kW}$ .

**EVALUATE** Solving for  $\Delta T$  gives

$$\Delta T = \frac{2.5 \text{ kW}}{120 \text{ W/°C}} = 21^\circ\text{C}$$

With the basement at 15°C, the water temperature is then 36°C.

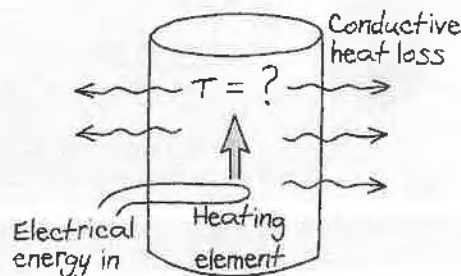


FIGURE 16.13 Balance between the heat supplied by the electric element and the conductive loss determines the water temperature.

**ASSESS** Is this answer reasonable? Not if you want a hot shower: our answer is 1°C below body temperature! But we're told the insulation is bad, so it's time for a new water heater!

$$2500 \frac{\text{J}}{\text{s}} \text{ in} \quad H = \frac{k \cdot A}{x} \cdot (T_v - T_k)$$



*Finn Haugen*

1

*Regulering  
av dynamiske  
systemer*

**TAPIR**

## 2.5 Termiske systemer

Ved modellering av termiske systemer benytter vi balanseloven til å sette opp *energibalanser*. Begrepet energi omfatter blant annet temperaturavhengig energi, som vi kan kalle termisk energi, og kinetisk og potensiell energi, og man må generelt regne med at det foregår overganger fra en energiform til en annen i et system. For eksempel kan kinetisk energi via friksjon gå over til varme og dermed påvirke systemets termiske energi. I mange termiske systemer er det tilstrekkelig nøyaktig å kun la energibalansen omfatte den termiske energien, og vi neglisjerer da overgangen fra kinetisk og potensiell energi.

Balanseloven (2.1) benyttet på termiske systemer blir:

**Energibalanse:**

$$\frac{dE}{dt} = \sum_i Q_i \quad (2.25)$$

der

$E$  [J] er systemets "termiske" energi.

$Q_i$  [W=J/s] er energiinnstrømning(er).

Denne energien vil være proporsjonal med temperaturen og massen (eventuelt volumet):

**Termisk energi:**

$$E = cm(T - T_0) \quad (2.26)$$



der

$T$	[°C]	er systemets temperatur.
$T_0$	[°C]	representerer nullnivået for energien.
$m$	[kg]	er massen.
$c$	[J/(kg K)]	er spesifikk varmekapasitet.

Nullnivået  $T_0$  kan vanligvis settes lik null. Dette blir demonstrert i eksempel 2.6 nedenfor.

Nedenfor beskrives noen måter energitransport kan foregå på. (Vi skal straks bruke de matematiske formlene som blir "listet opp" på et konkret eksempel.)

I systemer med gjennomstrømning av væske, som for eksempel varmevekslere, følger det en energiinnstrømning med masseinnstrømningen og en energiutstrømning med masseutstrømningen. Dette er *varmeledning*. Energiinnstrømningen er gitt ved

**Varmeledning:**

$$Q = cw(T_i - T_0) :$$

(2.27)

der

$Q$	[W=J/s]	er tilført energi pr. tidsenhet.
$T_i$	[°C]	er temperaturen i innstrømningen.
$T_0$	[°C]	representerer nullnivået for energien.
$w$	[kg/s]	er masseinnstrømningen.
$c$	[J/(kg K)]	er spesifikk varmekapasitet.

(Produktet av  $c$ ,  $w$  og  $(T_i - T_0)$ , som utgjør et ledd i  $Q$  i (2.27), får enhet J/s = W, altså "energi pr. tidsenhet", som er den enheten venstresiden i energibalansen må ha. Nettopp en slik "dimensjonsanalyse" kan være nyttig når man skal kontrollere at man har fått med alle leddene i et uttrykk som inngår i en eller annen fysisk balanse.)

Helt tilsvarende blir uttrykkene for energiutstrømningen (varmeledningen ut av systemet), det er bare å bytte ut  $T_i$  med  $T_u$  (temperaturen i utstrømningen) i (2.27). Merk at  $T_u$  oftest vil være lik temperaturen inne i tanken, altså at  $T_u = T$ .

*Varmeovergang* er en annen måte energi transporteres på. Det vil være varmeovergang gjennom "veggen" mellom to nabosystemer. Energiinnstrømningen til et system fra nabosystemet (omgivelsene) er tilnærmet propor-

sjonal med temperaturdifferansen mellom systemene:

**Varmeovergang:**

$$Q_i = hA(T - T_{omg})$$

(2.28)

der

$Q_i$	[W=J/s]	er tilført energi pr. tidsenhet.
$T_{omg}$	[°C]	er nabosystemets eller omgivelsenes temperatur.
$T$	[°C]	er systemets egen temperatur.
$h$	[W/(m <sup>2</sup> K)]	er (areal-)spesifikt varmeovergangstall.
$A$	[m <sup>2</sup> ]	er arealet som varmeovergangen skjer gjennom.



# Newton's kjølelov og varmeovergang

## Mathematical formulation of Newton's law [\[ edit \]](#)

The statement of Newton's law used in the heat transfer literature puts into mathematics the idea that *the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings*. For a temperature-independent heat transfer coefficient, the statement is:

$$\dot{Q} = hA (T(t) - T_{\text{env}}) = hA \Delta T(t),$$

where

- $\dot{Q}$  is the rate of heat transfer out of the body (SI unit: [watt](#)),
- $h$  is the [heat transfer coefficient](#) (assumed independent of  $T$  and averaged over the surface) (SI unit:  $\text{W}/\text{m}^2\cdot\text{K}$ ),
- $A$  is the heat transfer surface area (SI unit:  $\text{m}^2$ ),
- $T$  is the temperature of the object's surface (SI unit: K),
- $T_{\text{env}}$  is the temperature of the environment; i.e., the temperature suitably far from the surface (SI unit: K),
- $\Delta T(t) = T(t) - T_{\text{env}}$  is the time-dependent temperature difference between environment and object (SI unit: K).

The heat transfer coefficient  $h$  depends upon physical properties of the fluid and the physical situation in which convection occurs. Therefore, a single usable heat transfer coefficient (one that does not vary significantly across the temperature-difference ranges covered during cooling and heating) must be derived or found experimentally for every system that is to be analyzed.

Formulas and correlations are available in many references to calculate heat transfer coefficients for typical configurations and fluids. For laminar flows, the heat transfer coefficient is usually smaller than in [turbulent flows](#) because turbulent flows have strong mixing within the [boundary layer](#) on the heat transfer surface.<sup>[6]</sup> Note the heat transfer coefficient changes in a system when a transition from laminar to turbulent flow occurs.



# varmeovergangstall

← VVS

Varmeovergangstall, også kalt varmeovergangskoeffisient, brukes for å karakterisere varmeutvekslingen mellom en materialoverflate og et fluid (gass eller væske) i kontakt med overflaten. Varmeovergangstallet er definert som varmestrømtetthet ( $\text{W/m}^2$ ) per grad ( $^{\circ}\text{C}$  eller  $\text{K}$ ) forskjell mellom overflatens temperatur og fluidets temperatur. Vanligvis benyttes symbol  $h$  for varmeovergangstallet, som har dimensjon  $\text{W}/(\text{m}^2\text{K})$ . Den inverse verdien  $1/h$  ( $\text{m}^2\text{K}/\text{W}$ ) kalles varmeovergangsmotstand.

**OGSÅ KJENT SOM** varmeovergangskoeffisient

Størrelsen på varmeovergangstallet vil være svært avhengig av i hvilken grad fluidet er i bevegelse og vil øke med økende fluidhastighet ved overflaten. Størrelsen vil også avhenge av en rekke andre forhold, som fluidets viskositet, varmeledningsevne og varmekapasitet, overflatens ruhet og orientering, samt strømningsstypen (laminær eller turbulent strøm).

Dersom fluidet er helt i ro vil varmeoverføringen skje ved ren varmeledning. Hvis fluidet er i bevegelse vil det i grenselaget mot overflaten også skje en varmetransport med massestrømmen. Dette kalles konvektiv varmetransport. Fluidstrømmen kan skyldes oppdriftskrefter på grunn av densitetsforskjeller forårsaket av temperaturforskjeller (kalles fri eller naturlig konveksjon) eller ytre krefter for eksempel fra vind, vifter eller pumper (kalles tvungen konveksjon). Ved naturlig konveksjon er varmeovergangstallet vanligvis i området  $5\text{--}25 \text{ W}/(\text{m}^2\text{K})$ . Ved tvungen konveksjon er variasjonsområdet vesentlig større, avhengig av strømningshastighet og fluidets egenskaper.

De fleste har erfart varmeovergangstallets avhengighet av fluidhastigheten ved at varmetapet fra hudoverflaten kan øke betraktelig når vindhastigheten øker – «følt temperatur» blir lavere.

I bygningssammenheng er det vanligvis varmeovergang ved overflater mot ute- eller inneluft, eller i luftfylte hulrom eller spalter som har interesse. For bygningsflater ute eller inne kan lufthastigheten variere mye både over tid og over flaten. I praksis benyttes målte gjennomsnittsverdier for frie flater som erfaringsmessig er av rimelig størrelsesorden. Utgangspunktet er da slike temperaturforskjeller mellom overflate og luft som vanligvis forekommer og aktuelle vindhastigheter utendørs og lufthastigheter innendørs. I hjørner og kroker vil luftstrømningen bli hindret og her kan vi lokalt ha betydelig lavere verdier for det konvekative varmeovergangstallet enn på frie flater.

Ved standardiserte beregninger av bygningsdelers varmegjennomgangskoeffisient (U-verdi)

benyttes vanligvis følgende verdier for varmeovergangsmotstand ( $1/h$ ):

- Utendørs flater:  $0,04 \text{ m}^2\text{K/W}$
- Innendørs med varmestrøm oppover:  $0,10 \text{ m}^2\text{K/W}$
- Innendørs med horisontal varmestrøm:  $0,13 \text{ m}^2\text{K/W}$
- Innendørs med varmestrøm nedover:  $0,17 \text{ m}^2\text{K/W}$

Den lave verdien for utendørs flater skyldes virkningen av vind. Ved varmestrøm vertikalt gir situasjonen med høyest temperatur øverst (varmestrøm nedover) mindre luftbevegelse, og altså høyere varmeovergangsmotstand, enn den omvendte situasjonen.

For velisolerte bygningskonstruksjoner har varmeovergangstallet marginal betydning. For bygningsdeler med høy  $U$ -verdi, som for eksempel eldre vinduer med enkelt eller dobbelt glass, har den imidlertid merkbar innvirkning, slik at varmetapet øker når det blåser ute.

**SKREVET AV:** Jan Vincent Thue (NTNU)

**SIST OPPDATERT:** 16. juli 2019, [se alle endringer](#)

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